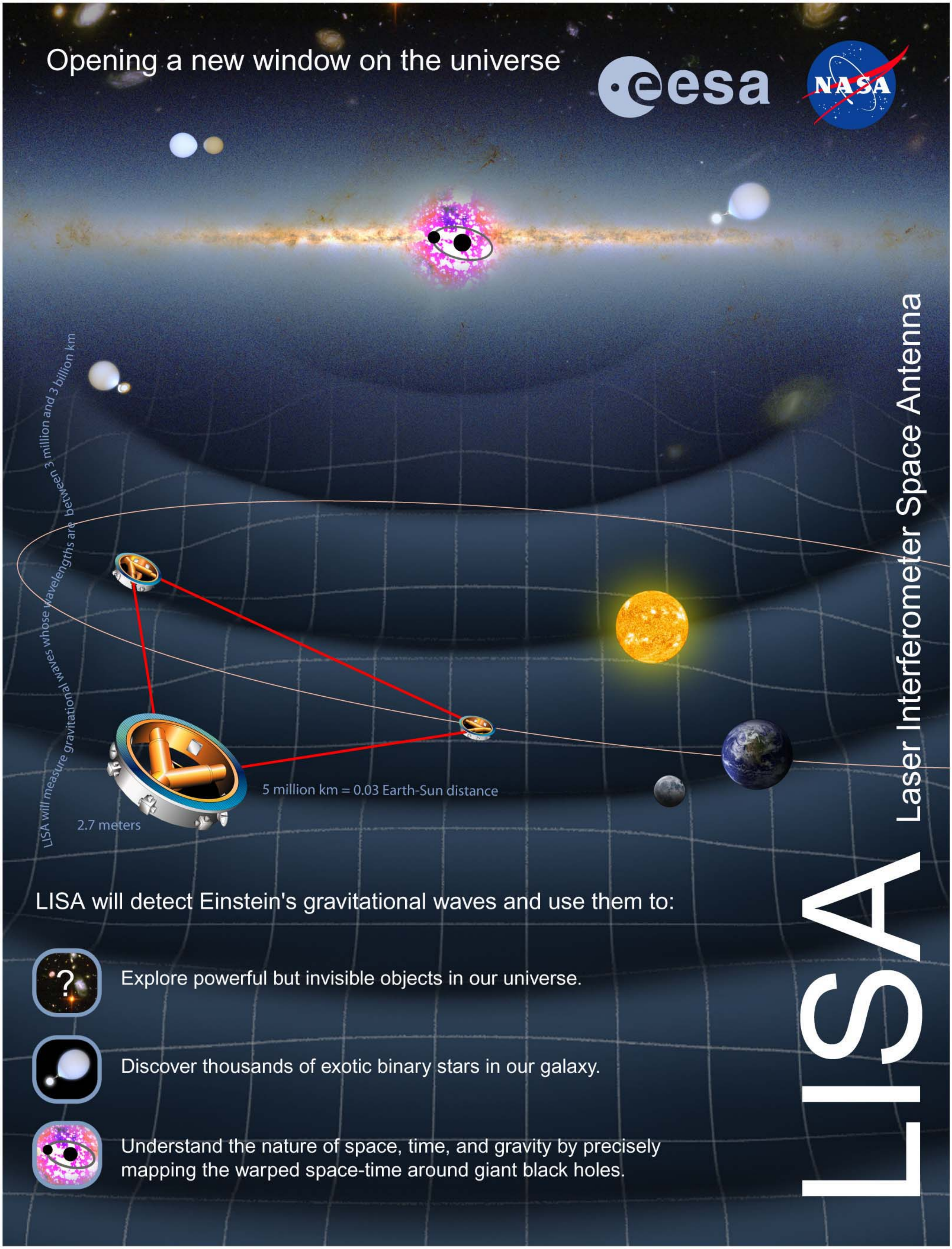


Opening a new window on the universe
esa
NASA
Laser Interferometer Space Antenna
LISA
LISA will measure gravitational waves whose wavelengths are between 3 million and 3 billion km
5 million km = 0.03 Earth-Sun distance
2.7 meters
LISA will detect Einstein's gravitational waves and use them to:
?
Explore powerful but invisible objects in our universe.
Discover thousands of exotic binary stars in our galaxy.
Understand the nature of space, time, and gravity by precisely mapping the warped space-time around giant black holes.

LISA and gravitational waves

The force of gravity creates a symphony

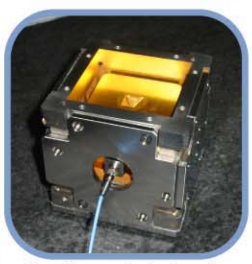
According to Einstein, *all* forms of mass and energy bend the fabric of space-time. When they move around, they create gravitational waves, vibrations in space-time that race outward at the speed of light to fill the universe. The universe's heaviest and fastest-moving objects produce the strongest vibrations. LISA will provide us with ears to hear this symphony performed by whirling stars, colliding black holes, and perhaps cracking cosmic strings and the explosive early universe.

LISA will reveal a universe unseen by telescopes

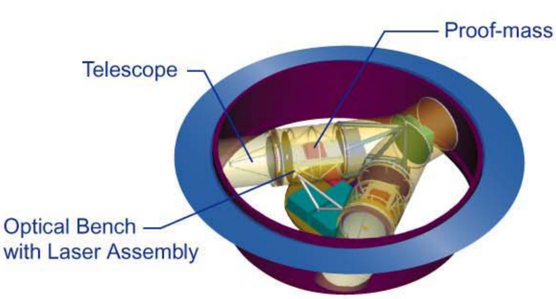
Until now, astronomers have studied our universe with electromagnetic radiation (visible light, radio waves, X-rays,...) emitted by luminous objects such as stars, galaxies, and the heated gas between them. But a controlling majority of the universe emits no such radiation—black holes, cold dead stars, dark matter, dark energy, quantum fields in the early universe and perhaps in extra dimensions of space. LISA will use gravitational waves to probe the workings of these powerful and influential cohabitants of our universe.

How LISA works: bobbing in the ocean of space and time

LISA, the Laser Interferometer Space Antenna, is a trio of spacecraft orbiting the sun. As gravitational waves pass LISA, they slowly squeeze and stretch the space between the spacecraft. LISA measures this stretch and squeeze with laser interferometers that monitor tiny changes in the times laser beams take to travel from metal cubes ("proof masses") floating inside one spaceraft to identical proof masses in each of the other craft, five million kilometers distant. This enormous distance, 400 times the diameter of Earth, was chosen to match the lengths of waves from the most powerful expected sources. Sufficiently accurate measurements over such large distances can be achieved only in the vast stillness of space.

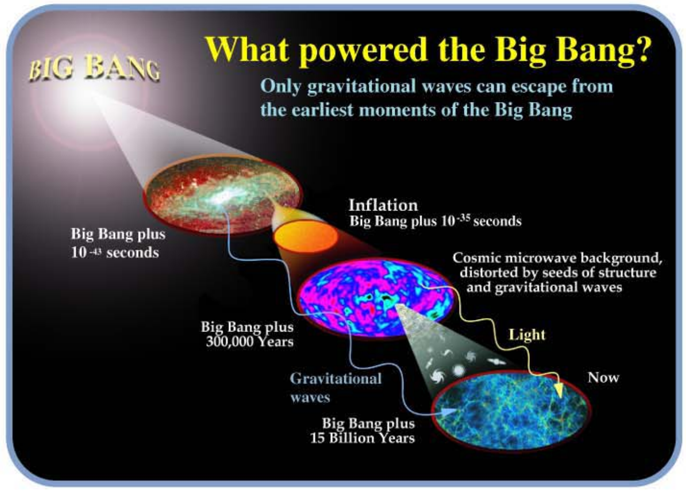


Proof mass in its housing



Explore the invisible universe

Our expanding universe was once unimaginably hot and dense— far hotter and denser than anything we can create in the greatest of particle accelerators. Physicists believe that during this first 10^{-12} second of expansion, the forces of nature developed and matter began to take on its present form. Yet during this vital era all light was trapped by matter. No telescopes, no matter how powerful, can ever see what happened then.



Fortunately, gravitational waves were not trapped in this way. They can reach us directly from as far back as 10^{-36} second after the Big Bang. LISA will explore directly these hidden stages in the growth of our infant universe. LISA will also hunt for exotic dark components of our local universe predicted by modern physics — cosmic strings and superstrings, some forms of dark matter, and (through precise measurements of distances to binary black holes) dark energy.

Discover exotic binary stars

Binary stars will be the most numerous of LISA's gravitational wave sources. Astronomers have seen several pairs of nearby white dwarfs that orbit each other in just minutes. Their strong gravitational waves will provide prompt on-orbit validation of LISA's operation. If the waves LISA measures from these white dwarfs were to differ from the predictions of Einstein's general relativity, it would shake the very foundations of gravitational physics.

Because white dwarfs are faint, astronomers can see only the nearest few pairs. By contrast, LISA will hear and measure individually all the thousands of binary stars in our Milky Way whose orbital periods are shorter than several minutes. This complete census will give us unprecedented insight into the evolution of close pairs of stars and of the progenitors of some types of supernovae, neutron stars, and black holes. LISA will also hear millions of binaries with longer orbital periods, so numerous that their waves will blend together into noise.

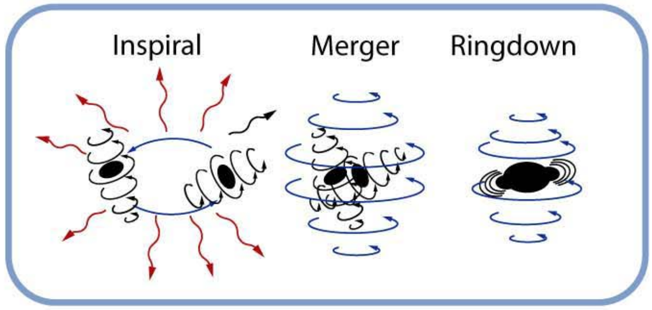
Understand space, time and gravity: Supermassive black holes

There is compelling astronomical evidence that almost every galaxy, including our own Milky Way, harbors at its center at least one super-dense object, a million to a billion times heavier than our Sun. These objects are presumed to be black holes, predicted by general relativity, but the evidence to date is only circumstantial. LISA will map in detail the twisting space-times around these supermassive objects, and so test the black-hole hypothesis and confirm, enhance, or revise Einstein's theory.

Collisions of supermassive black holes

Telescopes show that when the universe was young, it was filled with multitudes of small galaxies which merged over time to form our modern galaxies. Many of the small galaxies harbored giant black holes. These sank to the merged galaxies' centers, found each other, and collided, releasing in minutes as much energy as would the annihilation of thousands of suns — the most violent events our universe has experienced since its birth. Where did that huge energy go? Into gravitational waves so strong that LISA could detect them, even from the farthest sources we believe exist.

LISA is sensitive enough to detect waves from some impending collisions months in advance, so that electromagnetic telescopes can be trained on the appropriate patch of sky. Analysis of the gravitational-wave signals, several of which might arrive each year, will reveal the wobbling inspiral of the two black holes, the violent contortions of space-time as their event horizons collide, and the final smoothing of space-time around the newly-formed single black hole. Analysis of these records will provide an unprecedented workout for black-hole theory and for Einstein's theory of General Relativity in its full dynamical, strong-field glory.

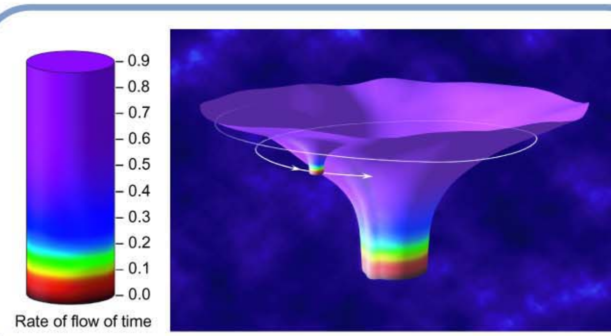


Growth of black holes in galactic nuclei

Little is known about black holes with masses between a hundred and a million times the mass of the sun. These *intermediate-mass* black holes may have grown by aggregation of the universe's first heavy objects, and in turn may have been the seeds that grew into supermassive black holes. LISA will search for waves from their mergers, to show us how supermassive black holes came to be.

Capture of stars by supermassive black holes

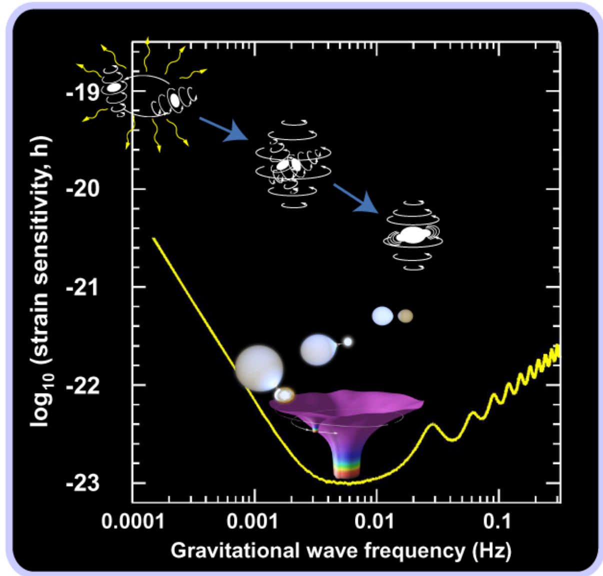
A dense cluster of stars surrounds the giant black hole in the core of most galaxies like our own. Occasionally, a compact star or stellar remnant in the cluster will careen around others, be flung downward, and get dragged into a tight orbit near the giant hole's horizon. LISA will observe waves from the last few years of this object's life, the million orbits before it plunges into the abyss. These waves encode a detailed map of the giant hole's warped space-time. LISA's census of the number and masses of inspiralling objects and of precise black-hole properties will inform us about the hidden inhabitants of the cores of galaxies and their interactions.



Since the only significant force acting on the compact object is gravity, any discrepancy between the predicted and the measured wave signals, even a fraction of a percent, could point to a flaw in black hole theory, or it could tell us that the supermassive object was not a black hole, but something novel. In fact history suggests that once LISA opens her new window on the universe, her most dramatic discoveries will be the ones of which mankind has not yet even dreamed.

Gravitational waves outside the LISA band

From AM radio waves the size of city blocks, through visible light, to atom-sized X-rays, electromagnetic waves come in a vast range of wavelengths. Gravitational waves do, too. The huge, powerful sources sought by LISA produce gravitational waves with wavelengths between 3 million and 3 billion km (frequencies 0.1 - 0.0001 Hz). Earth is covered with moving things that drown out these slow signals, which is why LISA must be in space. Neutron stars and small black holes produce gravitational waves of higher frequencies (10 - 1000 Hz; 30,000 to 300 km wavelength) which will be discernible despite Earth-based noise and are sought by a network of ground-based detectors: LIGO, GEO600, VIRGO. Indirect evidence for gravitational waves has come from timing the orbits of several pairs of radio-emitting neutron stars (pulsars). Since the 1974 discovery of the first such pair, the orbits have been tightening precisely as relativity predicts would be caused by gravitational waves carrying off orbital energy (at wavelengths longer than LISA will measure)— a measurement that won Hulse and Taylor a Nobel Prize. Still longer waves, nearly as large as the visible universe, are predicted to have been produced in the Big Bang, and astronomers are seeking their imprint on the polarization of cosmic microwaves.



The curve shows LISA's dimensionless gravitational wave strain sensitivity at S/N (Signal/Noise) = 5 for one year's observation of a periodic source in an average direction on the sky, as a function of the wave's frequency. Representative sources plotted are three phases (inspiral, horizon collision and ringdown) of the merger of a pair of black holes (10^6 and 3×10^5 times the sun's mass, at redshift 1; total S/N=2500), three white dwarf pairs 3000 light years away (left to right: orbital periods 33, 10 and 3.3 minutes; S/N=6, 80 and 210), and a compact object with the mass of the Sun spiralling into a million-solar-mass black hole, at redshift 0.2 (S/N=30).

Quick facts about LISA

LISA Pathfinder: ESA's LISA Pathfinder mission with ESA/NASA LTP/ST7 payloads will demonstrate the core technologies needed both for LISA's laser interferometers and for the "drag-free" spacecraft control that protects LISA's proof masses from disturbance.

LISA: The Laser Interferometer Space Antenna is a joint mission of NASA and ESA. Specifications below are per the baseline design of 2005 but are subject to change.

Launch and cruise: A single Delta-IV rocket lifts all three spacecraft, each with its own propulsion module. They reach their final solar orbits after a 13-month cruise.

Orbits: Each drag-free spacecraft is in an independent heliocentric orbit, trailing Earth by about 20 degrees.

Stationkeeping: There is no stationkeeping. The orbits are chosen to keep the spacecraft at the corners of a nearly equilateral triangle throughout the mission life.

Inter-spacecraft separation: About 5 million km (0.03 Earth-Sun distance, or 17 light-seconds).

Spacecraft:

• Size:	2.7-m diameter, 0.5-m thick
• Mass:	Under 700kg
• Orientation:	60 degrees to the Sun, constant.
• Power:	820W per spacecraft, from solar cells.
• Attitude and drag-free control:	Six thrusters, 4 to 30 microNewton each
• Mission lifetime:	Five years, minimum two years

Payload (per spacecraft):

Lasers (two): 1W diode-pumped 1064-nm Nd:YAG lasers, frequency-stabilized to an onboard ULE reference cavity and also to the inter-spacecraft arms.

Proof masses (two): 2-kg Au-Pt cubical proof masses. Electrostatic actuation perpendicular to the measurement axes. Charge control by UV illumination.

Telescopes (two): 40-cm diameter, f/1, used both to transmit and receive.

Measurement and error budget:

Measurement: Optical heterodyne. The received laser beam (about 10^{-10} W) is mixed with about 1mW of local laser light on a quadrant photodiode. Measurements from all three pairs of spacecraft are combined using time-delay interferometry to synthesize two separate Michelson interferometers and a third separate Sagnac interferometer.

Optical-path errors: Caused by detector shot noise, pointing jitter, *etc.*, total not to exceed 2×10^{-11} m/$\sqrt{\text{Hz}}$ over the LISA bandwidth.

Acceleration errors: Caused by unmeasured residual forces on proof masses. Total not to exceed 3×10^{-15} (m/s^2)/$\sqrt{\text{Hz}}$ from 0.1 to 1mHz. Divide by $(2\pi f)^2$ for resulting displacement error.

Strain sensitivity: See figure. Both wave polarizations h_+ and h_x can be measured for long-lived sources.

Source direction localization: Below 1 mHz or lifetime < months: degrees
Above 10 mHz and lifetime > months: arcminutes

For more information on LISA:

http://lisa.nasa.gov

http://sci.esa.int/home/lisa

For technical and scientific details, see:

http://www.srl.caltech.edu/lisa

LISA is an ESA/NASA joint project. It is a flagship mission of NASA's Beyond Einstein program and of ESA's Horizon 2000+ program. NASA will supply the spacecraft and launch vehicle. European partners will contribute much of the scientific instrumentation and the interplanetary propulsion systems to LISA. In addition, Europe is leading the LISA Pathfinder mission. NASA's Jet Propulsion Laboratory will supply the NASA ST-7 test package on LISA Pathfinder and the scientific instrumentation and operations support for the main LISA mission. NASA's Goddard Space Flight Center will manage the mission for NASA and will provide the spacecraft and final integration.

European Space Agency

National Aeronautics and Space Administration